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14. ABSTRACT
The US Army Corps of Engineers' (USACE) Virtual Autonomous Navigation Environment (VANE) is a physics-based, multi-scale numerical testbed designed to quantitatively and accurately predict sensor and autonomous system performance in a simulation environment. The work presented here captures progress on an initial empirical evaluation of how well the current VANE system is able to reproduce a real autonomy system's perception performance. Findings will directly guide continuing development of VANE, while beginning to

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Report Title

Empirical Evaluation of the Virtual Autonomous Navigation Environment

ABSTRACT

The US Army Corps of Engineers' (USACE) Virtual Autonomous Navigation Environment (VANE) is a physics-based, multi-scale numerical testbed designed to quantitatively and accurately predict sensor and autonomous system performance in a simulation environment. The work presented here captures progress on an initial empirical evaluation of how well the current VANE system is able to reproduce a real autonomy system’s perception performance. Findings will directly guide continuing development of VANE, while beginning to develop a suite of example sensor models and virtual environments.

This first experiment focuses on testing world modeling and sensor simulation. Data was collected from the Crusher autonomous vehicle, developed under the DARPA UPI program. Some sensor data was collected and manually processed to produce a VANE scene model. Crusher was again driven through the real scene to collect real sensor data as the baseline sensor data. The positions of the sensors were extracted and was used to generate a VANE simulation to exactly match Crusher's path. Both datasets were fed to an offline version of Crusher's autonomous perception software. The outputs from the two separate input data sets were compared. The results indicate good agreement between the outputs, especially on solid ground and solid objects. Differences were observed in the areas of vegetation, an area requiring further work to improve modeling and simulation of the sensors. Greater accuracy will also be required in the ground truth data, which was collected at WAAS GPS quality rather than RTK2 quality.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Number of Papers published in peer-reviewed journals: 0.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Brett Browning	0.10	No
Peter Rander	0.05	No
FTE Equivalent:	**0.15**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

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Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Validating VANE for UGVs

31 MAR 2009

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Outline

- UGV's and simulation
- Problem approach
- Real robot data
- Simulated results
- Cost map Comparisons
- Conclusions

UGV Autonomy Systems

NREC Vehicle "Crusher", performing navigation tasks for Darpa UPI Field Testing

Navigating a ravine at Fort Bliss

Complex system in non-trivial terrain. Expensive and time consuming to test

Autonomy System Basics

Perception/Modeling

Cost map

Path Planning

Images, XYZ points, …

Speed +
Steering

Sensor Server

Vehicle Controller

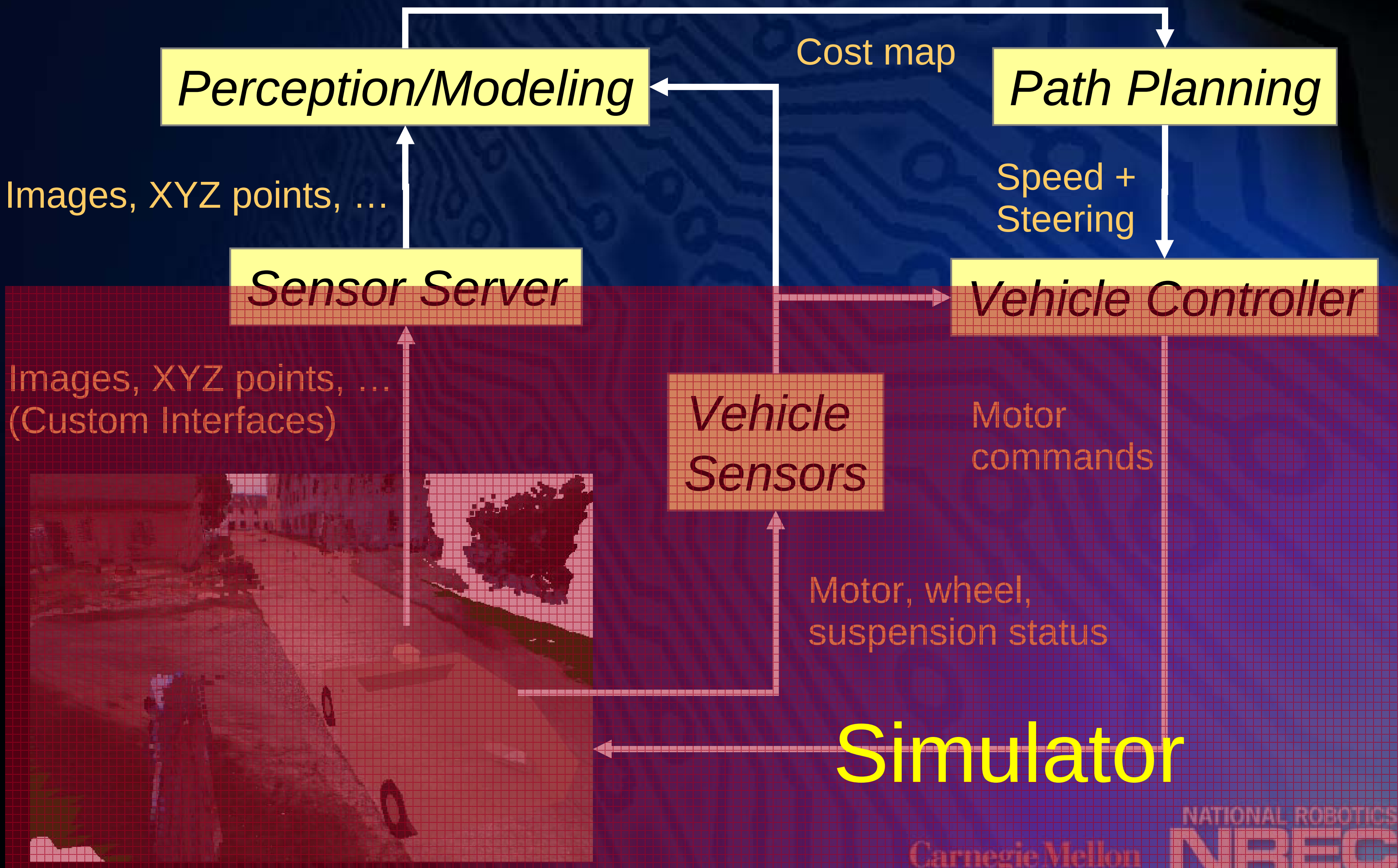
Images, XYZ points, …
(Custom Interfaces)

Vehicle Sensors

Motor
commands

Motor, wheel,
suspension status

Autonomy System Basics

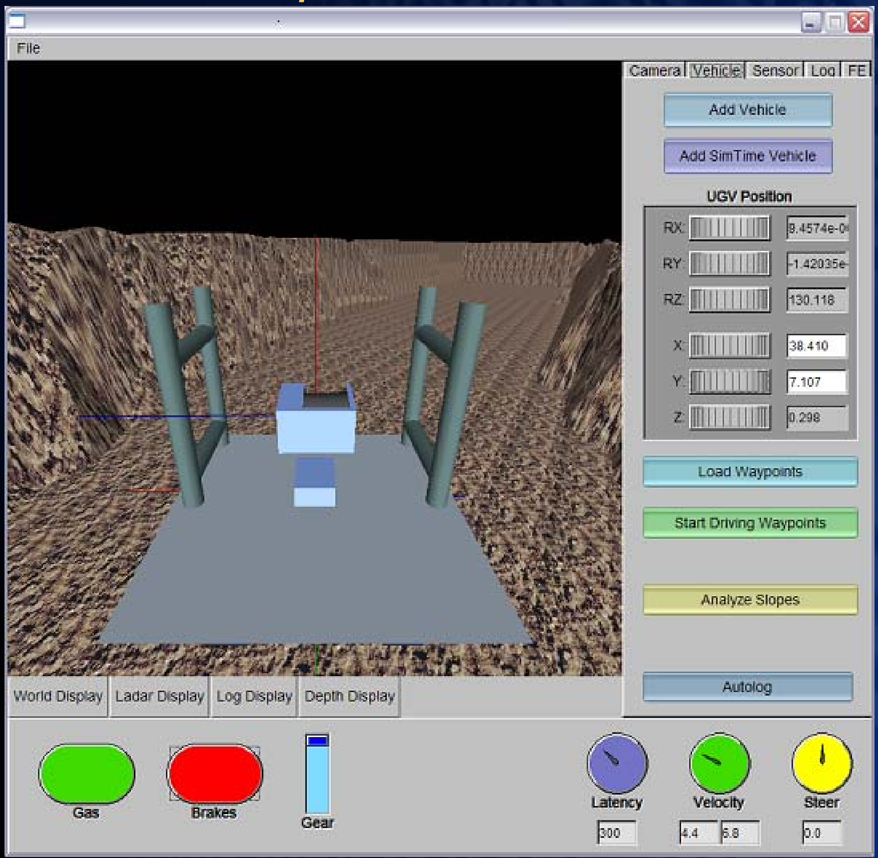


Simulation as a Test Harness

VERSaT 1: DARPA PerceptOR Program

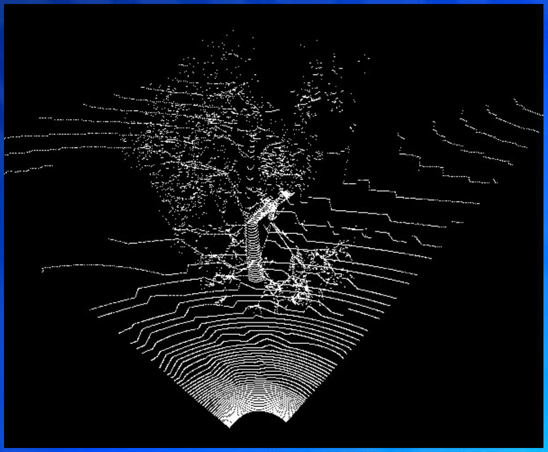
Virtual Environment for Robotic Simulation and Test

Operator GUI



Visual

Rendering of simulated ladar scans

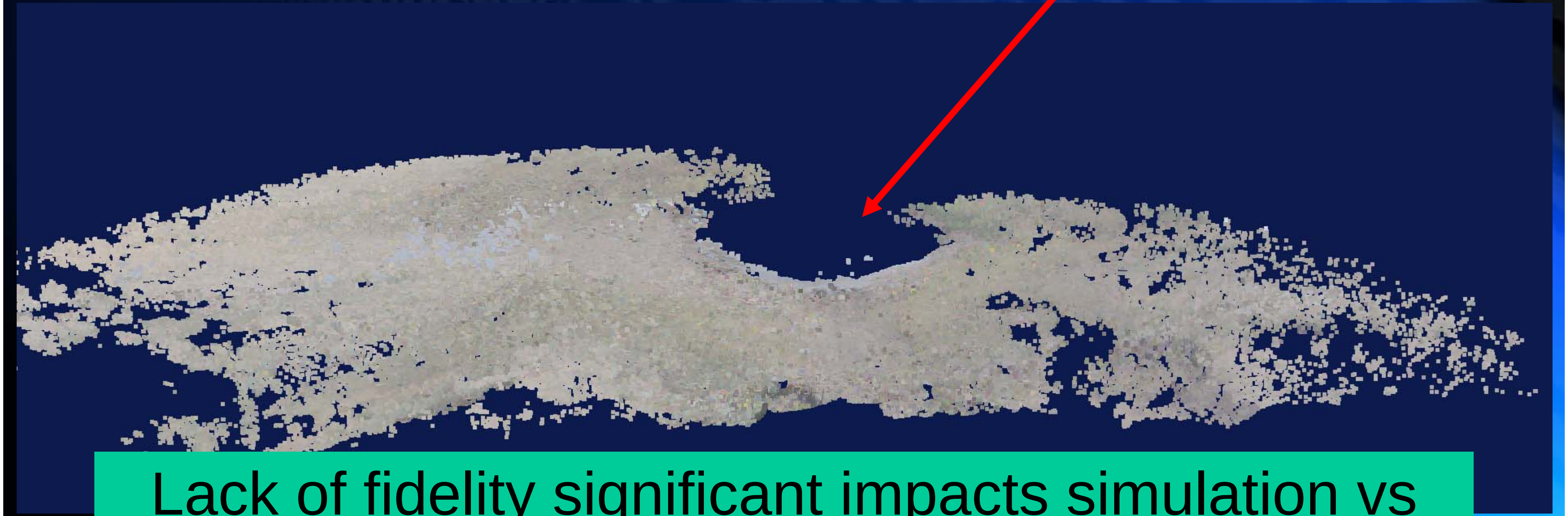


VERSAT2 (NREC/TARDEC)

Main Challenge: Real-Time Fidelity

- Simulators are useful, but lack fidelity
- World
  - Limited polygons, e.g. no grass or similar (1 blade/mm^2 → 10^6 blades/m^2)
  - No mud, water, or similar…
- Ladar Sensors
  - No motion during scan (~13 msec staticshots)
  - No range or angular noise, with first return only
  - No attention/non-returns (reflectance, range, foreshortening, …)
- Imaging and Stereo sensors
  - Easy to add but difficult to model well
- Vehicle
  - No suspension, tire ground modeling, friction/dynamics modeling

Example from Real Data



Lack of fidelity significant impacts simulation vs real vehicle performance comparisons

VANE/NREC Effort

- Summary so far:
  - Simulation is very useful for UGVs, but fidelity gap limits its use and effectiveness
- However, ERDC's VANE is a high fidelity simulator derived from physics models
- VANE/NREC Project goal

Investigate if VANE can address fidelity gap and create realistic simulation environment

Evaluating VANE

- How do we evaluate simulator quality?
  - Run robot autonomy and evaluate resulting decisions
    - Should match real vehicle decisions in the real world
    - Path planning cost maps represent this knowledge

- NREC/ERDC approach
  - Simulation of a known world location and collect real data from that location
  - Compare cost maps generated by robot autonomy perception on simulated sensory data and real data

Outline

- UGV's and simulation
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Approach: Data Collection (NREC)

1. Collect field test data from a real UGV
   - Data stored to time-stamped logs

Crusher with sensors

6 Tilting LiDars
4 Camera "Cubes"
- 1xRGB Stereo head
- 1xNIR Camera
- 1xDark Red Camera

DGPS/RTK INS system
Suspension sensors
Many vehicle sensors
Calibrated models
NREC Autonomy SW

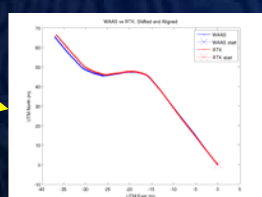
Developed on the UPI, UGCV, and PerceptOR programs

Approach: Model Generation

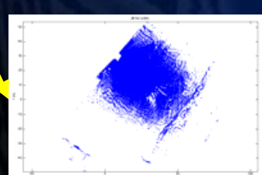
2. Extract world model data and generate VANE model of a real environment

Manual photos, world description, physical plant specimens

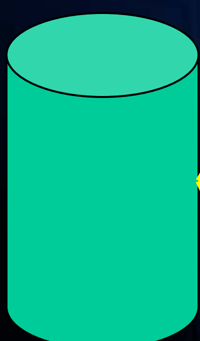
Vehicle imagery



Vehicle pose, sensor poses



Colorized-Ladar point cloud

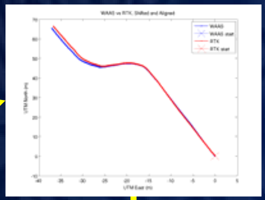


UPI Log

ERDC VANE model generation

Approach: Simulation (ERDC)

3. Run VANE Simulator and generate Simulated sensor data
   - Data registered to true vehicle sensor poses

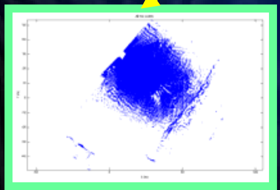


Extracted sensor poses and characteristics

UPI Log

ERDC VANE Simulator

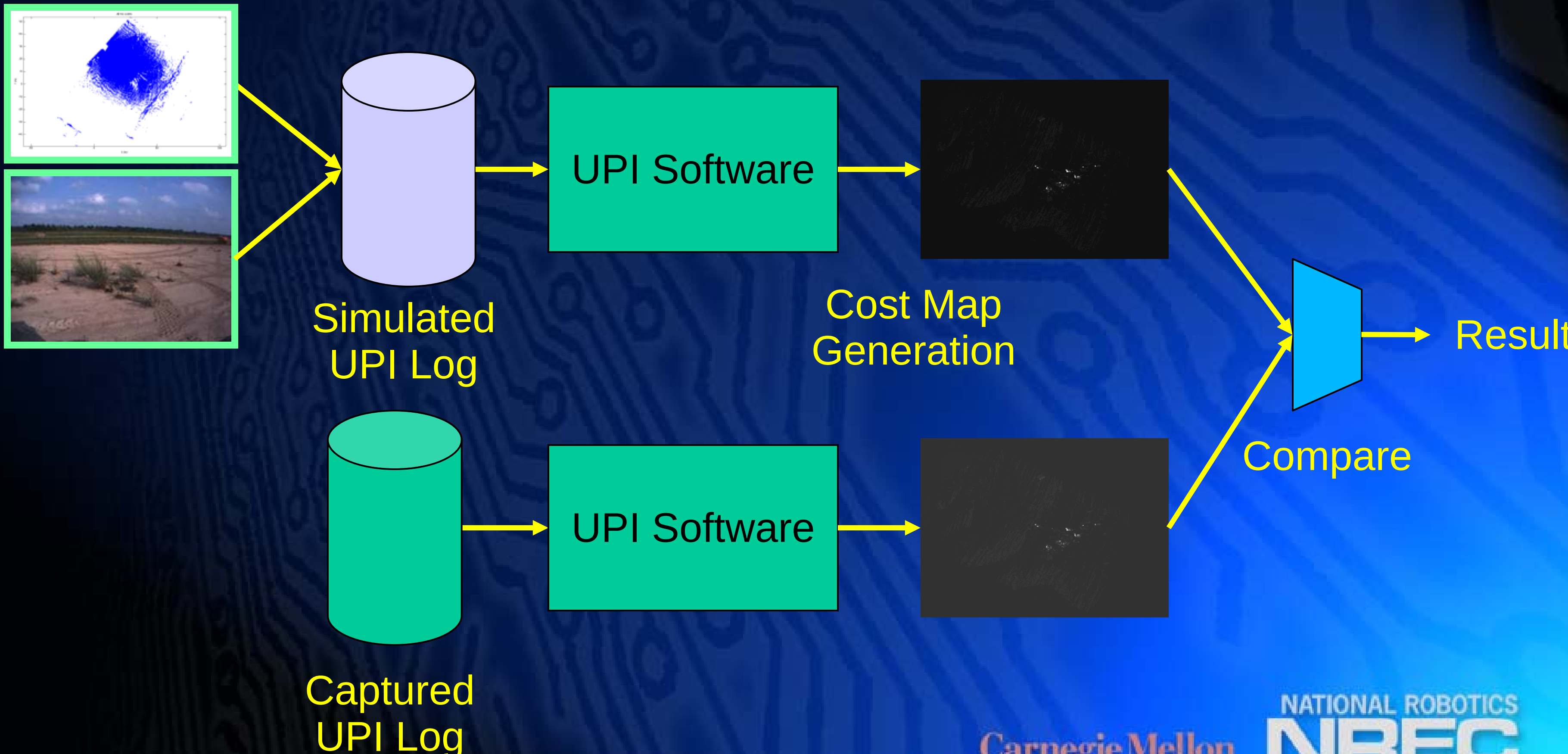
Generated Model



Simulated Sensor Data

Approach: Run Autonomy (NREC)

4. Run NREC autonomy SW on simulated and real data and compare cost maps



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Testing Site

- Fort Drum NY, June 2008, with an open field, rocks, small vegetation and hay bails
  - Positive obstacles (rocks, hay bails)
  - “Soft” obstacles (vegetation)

Navigable,
Low cost

Free space,
Very low cost

Obstacles,
High cost

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Data Collection

- 6 Runs recorded at around 6pm with NREC's Crusher vehicle
- Only forward looking sensors used
- 5 Runs used for model construction
  - Data provided to ERDC
- 1 run held back for evaluation
  - Sensor poses provided to ERDC for simulation

Data Collection Vehicle

NREC UPI "Crusher" Platform

Crusher with sensors

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Tilting Ladar Sensors

** All coords in UTM

X = Easting (m)

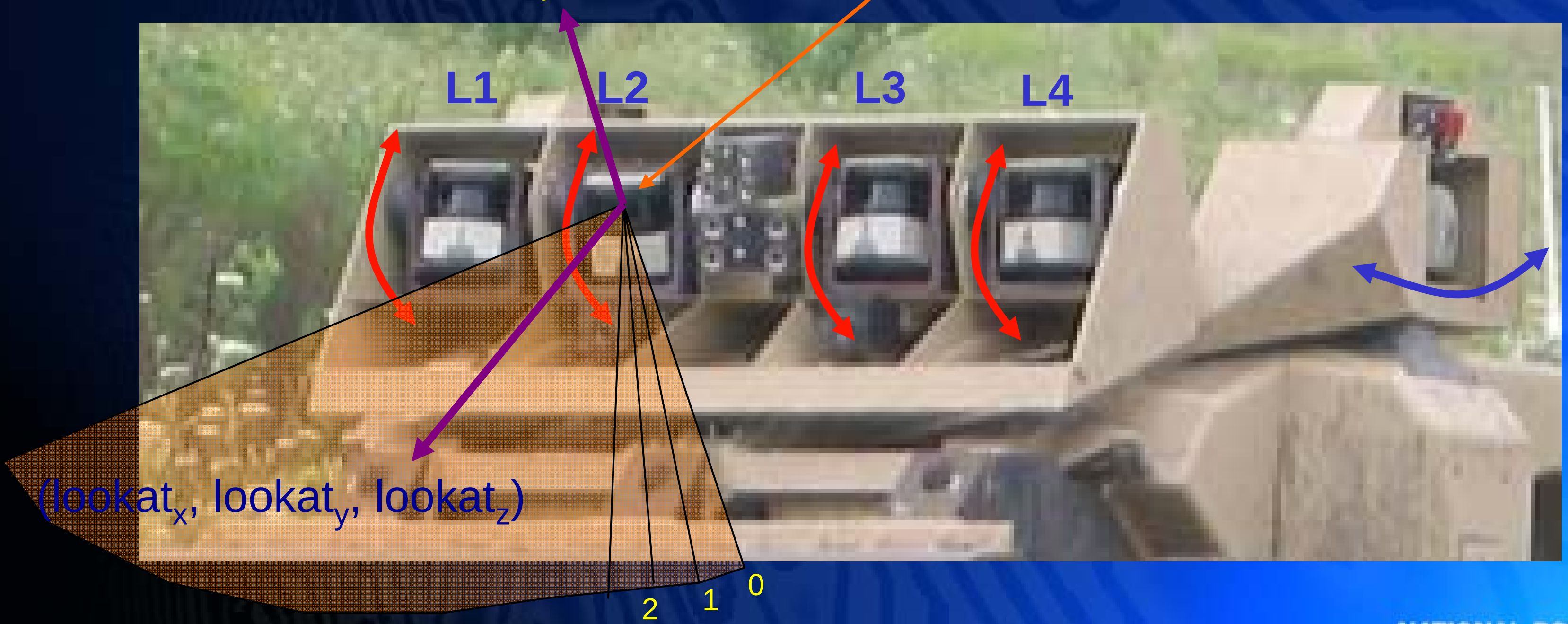
Y = Northing (m)

Z = Height (m)

Tilting ~45°
variable tilt rate

(up_x, up_y, up_z)

Pose: (x, y, z)

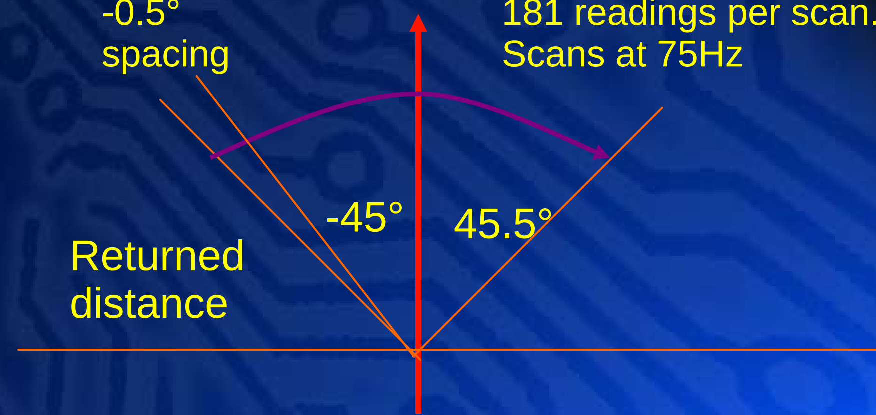


SICK LMS 291-S14 sensor. Scans a line with equal angle spacing. Each scan has 181 range readings left to right in 0.5º deg increments [-45º, 45.5º]. 75 line scans per second.

Sick Scan Model

Looking direction

View from above



23.2	15.1	29.6	…	100.0

Range values returned

Readings > 80m are ignored (ie. open space)

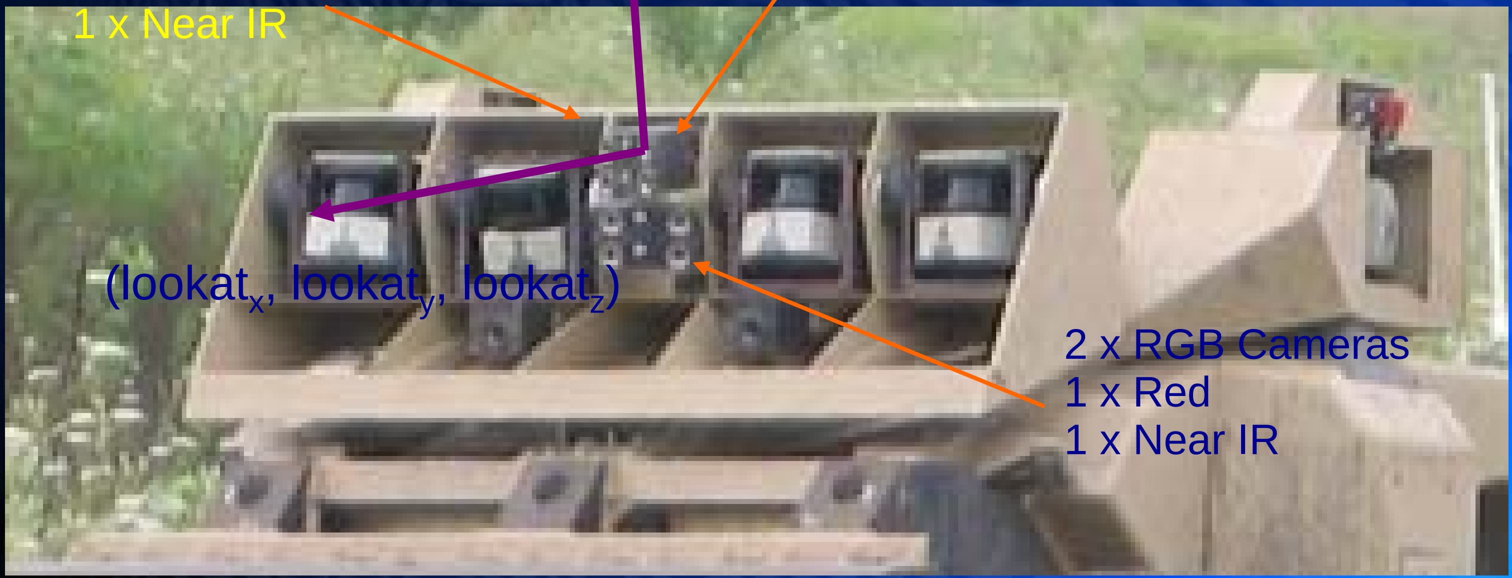
Camera Sensors

** All coords in UTM

X = Easting (m)

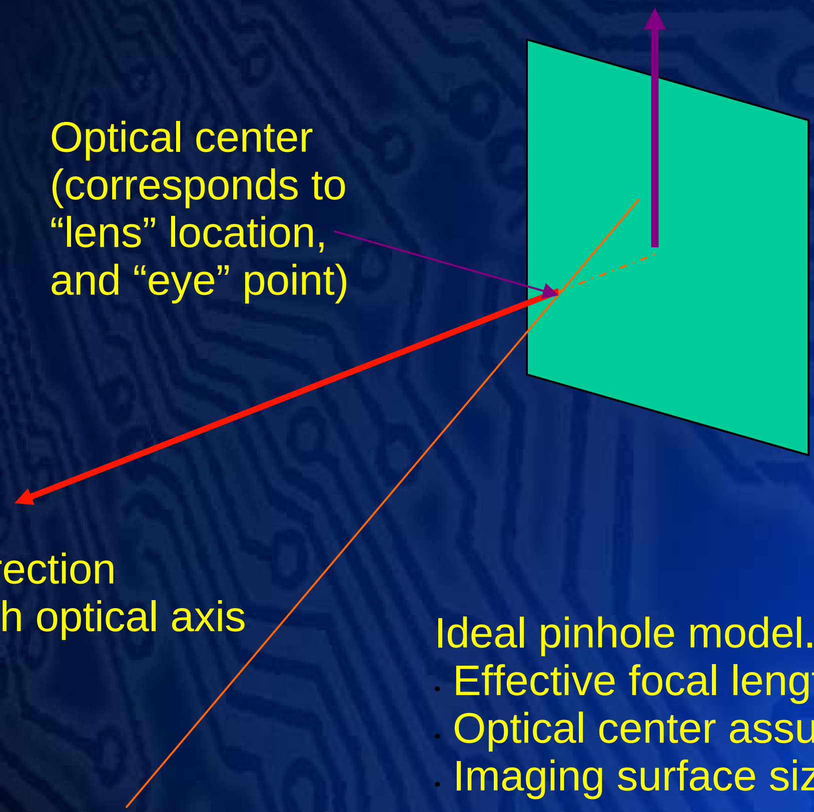
Y = Northing (m)

Z = Height (m)



Cameras based off the Bumblebee 1 stereo head from PointGrey. The color stereo head has two images (de-bayerized) with 512x384 RGB @ 15Hz. The second stereo head consists of two gray scale cameras with Red and NIR filters respectively. Each produces 1024x768 single channel @ 15 Hz

Perspective Camera Model



Ideal pinhole model. Defined by
- Effective focal length $f_x \sim f_y = f$
- Optical center assumed to be in center of image
- Imaging surface size (w, h)

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Real Sensor Data: Imagery

- Front looking right cameras

Left

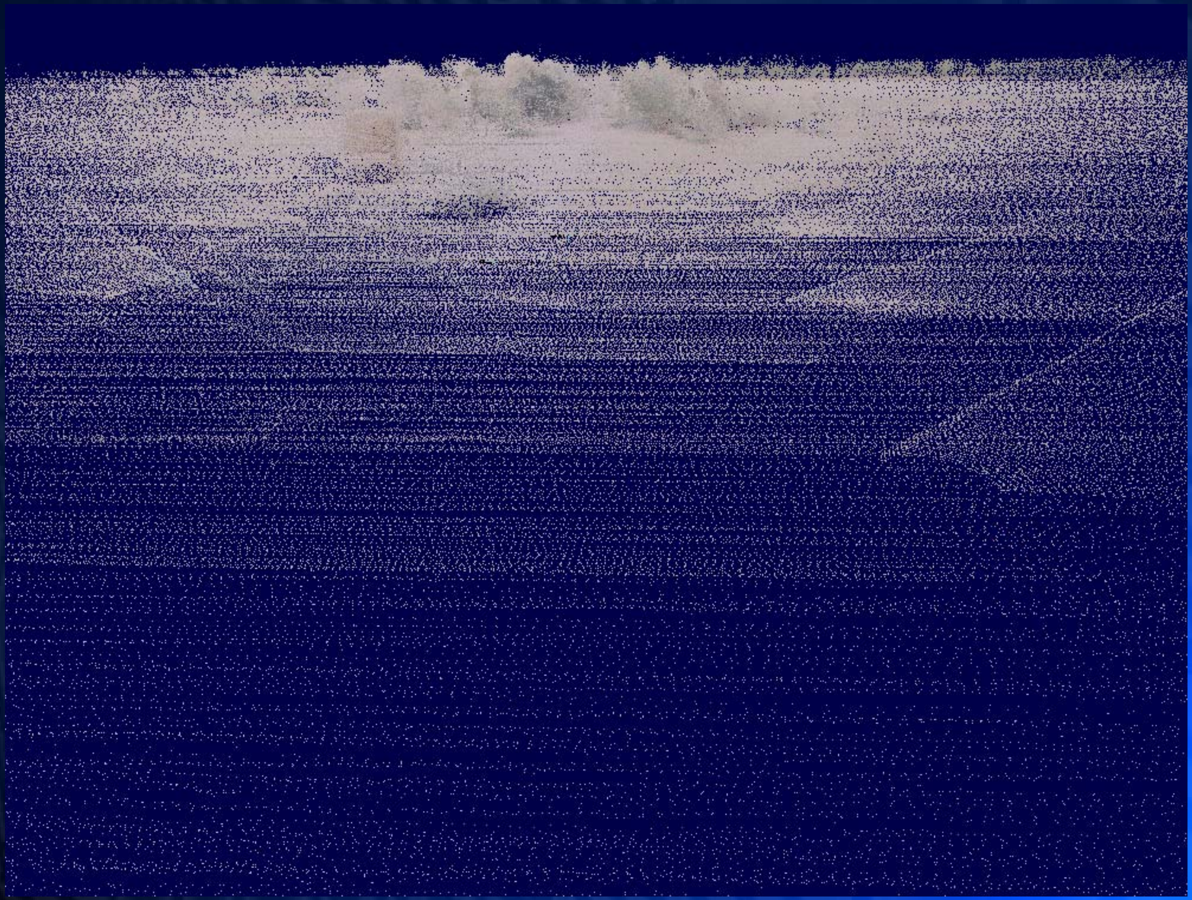
Right

Perspective affects, light scattering, diffuse lighting, …

Red

NIR

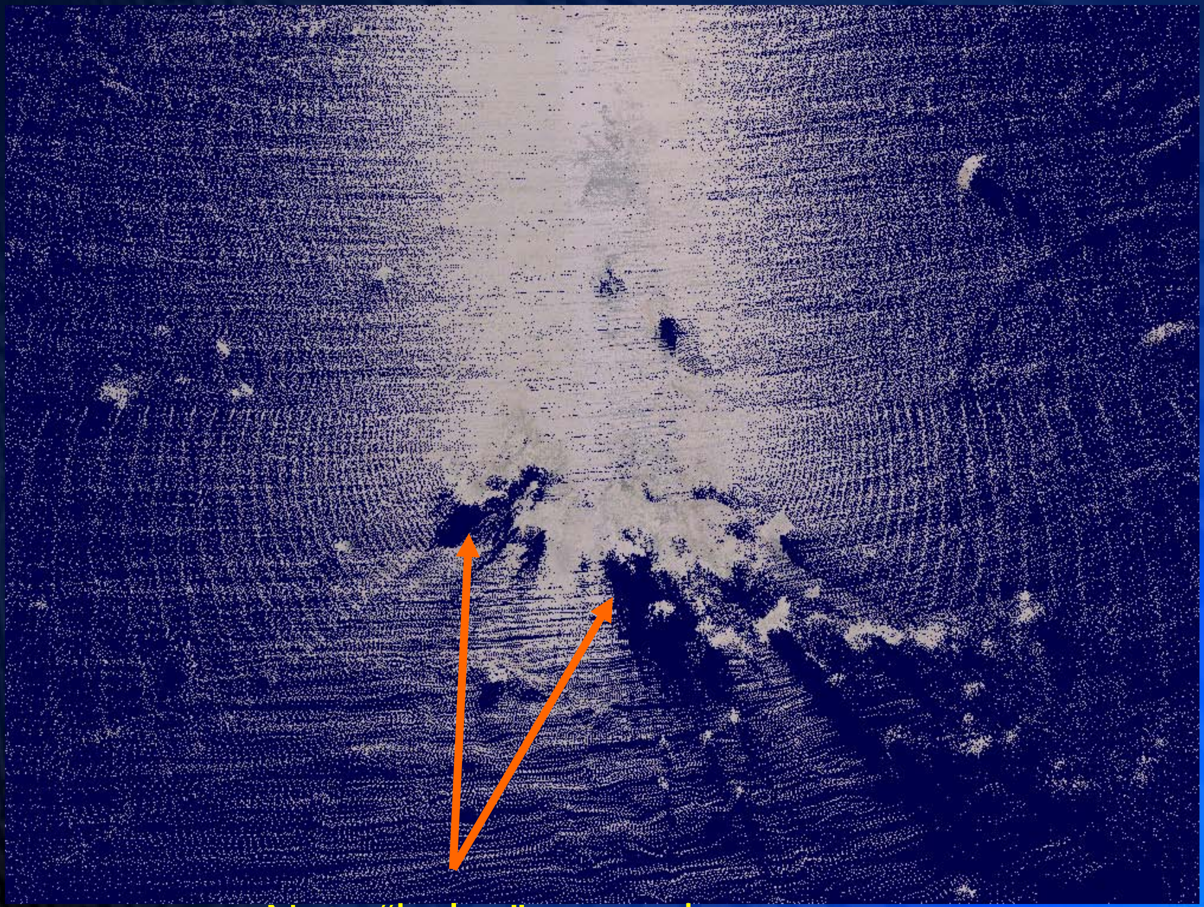
Real Data: Colorized Ladar Scans



Reconstructed from vehicle poses

Real Data: Colorized Range Data

Top view



Note “holes” caused by occlusion

Outline

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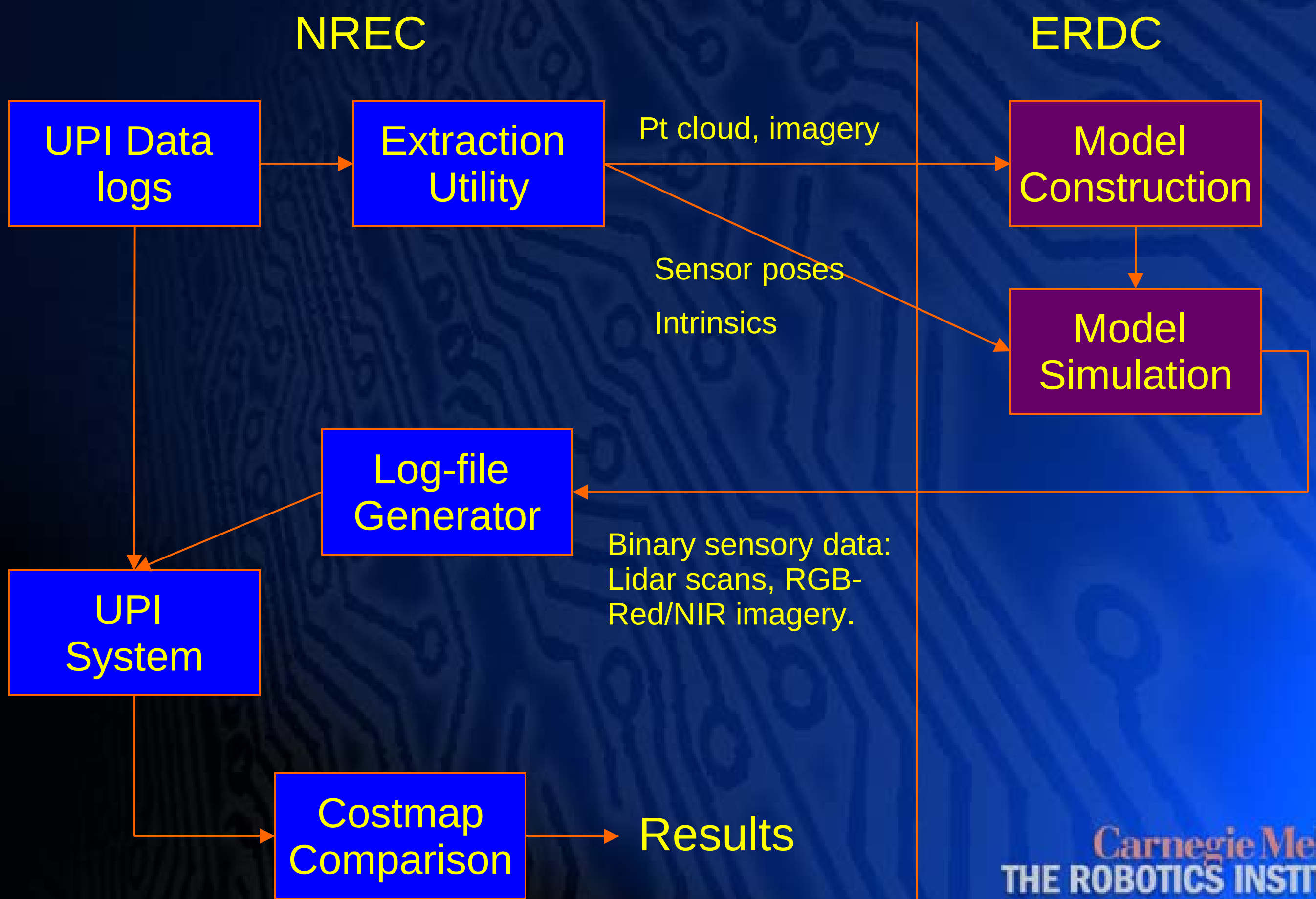
General Data Flow

- Sensor data for model and sensor poses for simulation sent to ERDC



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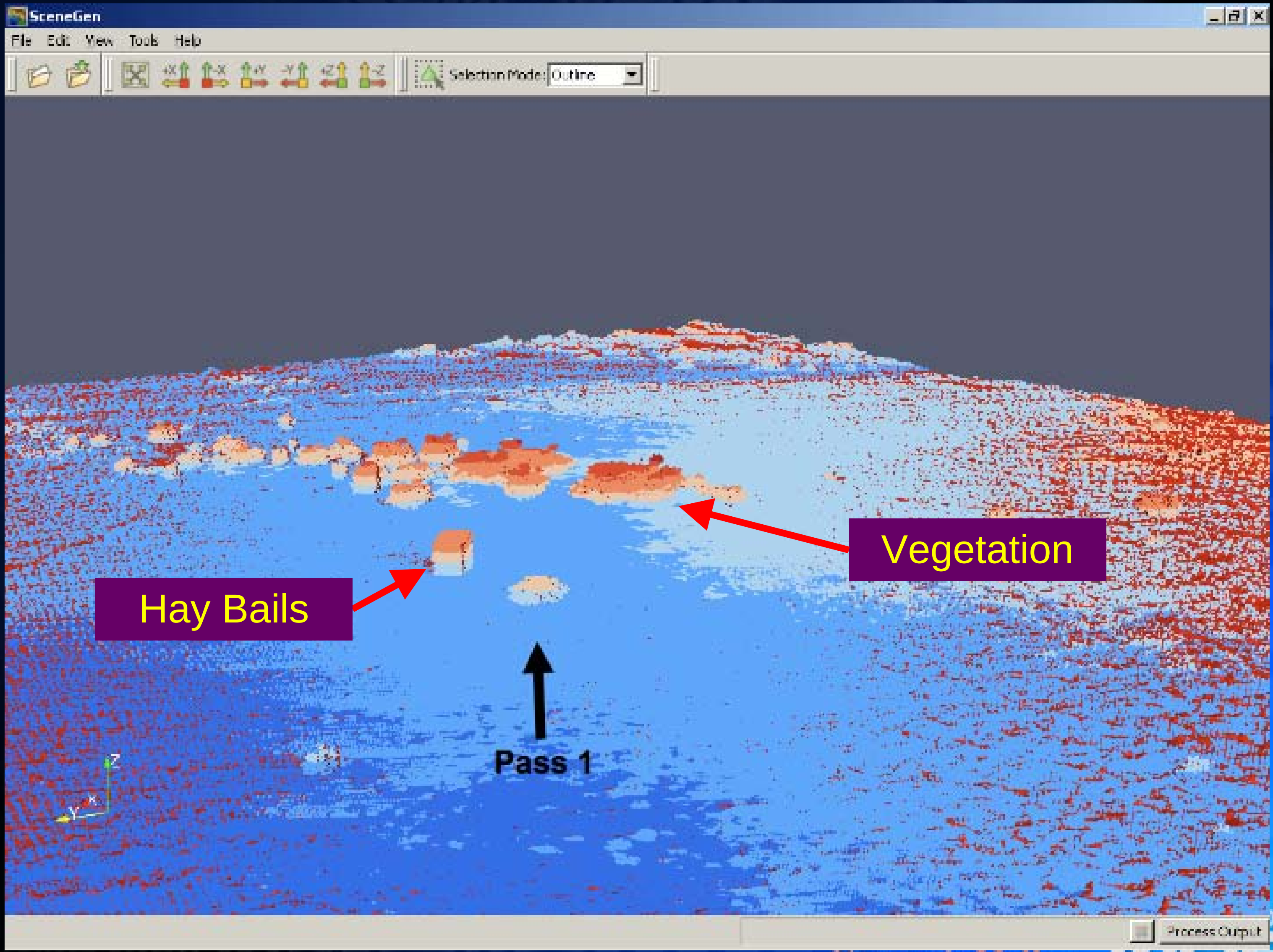
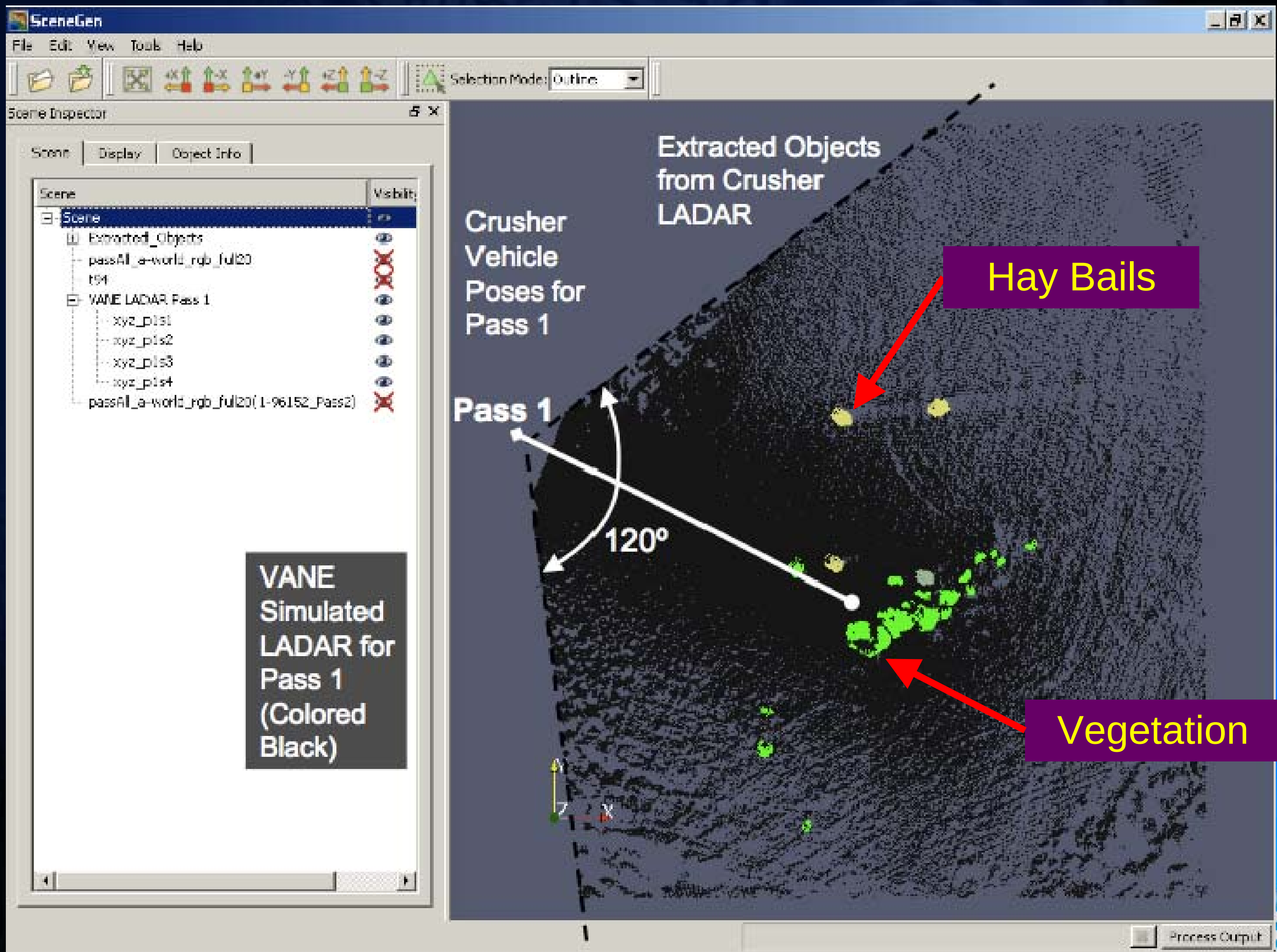
ERDC Generated Scene



ERDC Generated Scene



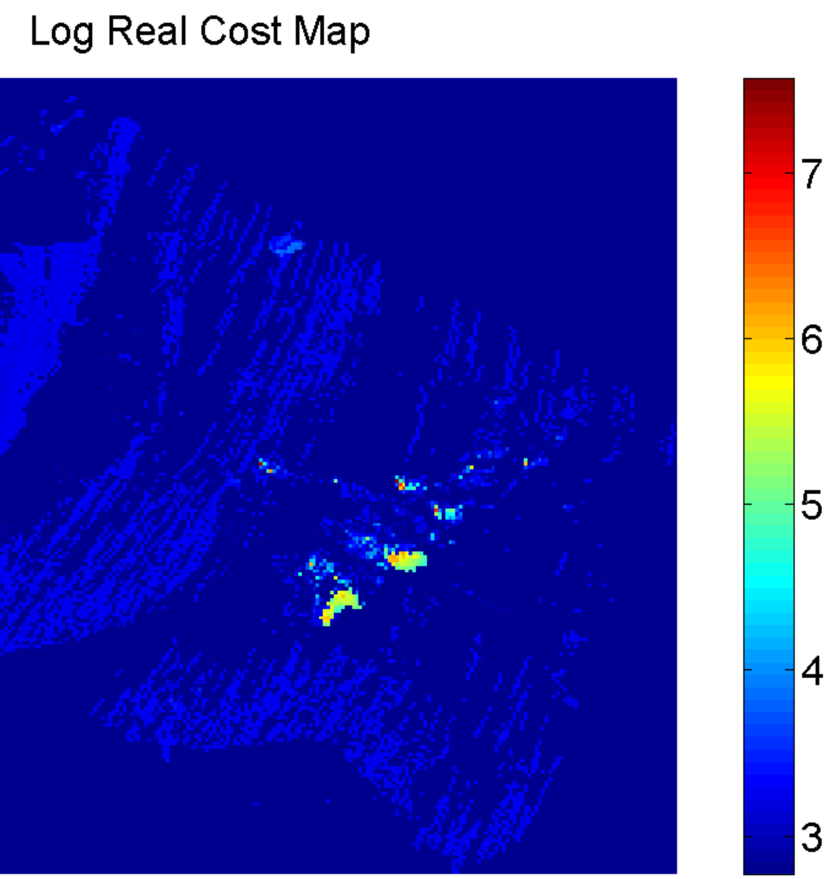
Cost Map Comparisons

- Run both sets of data through UPI System and produce cost maps
- Cost map representation:
  - Low cost represents “free space”
  - High cost represents “obstacles”
  - Vegetation often in between

Cost Map Analysis

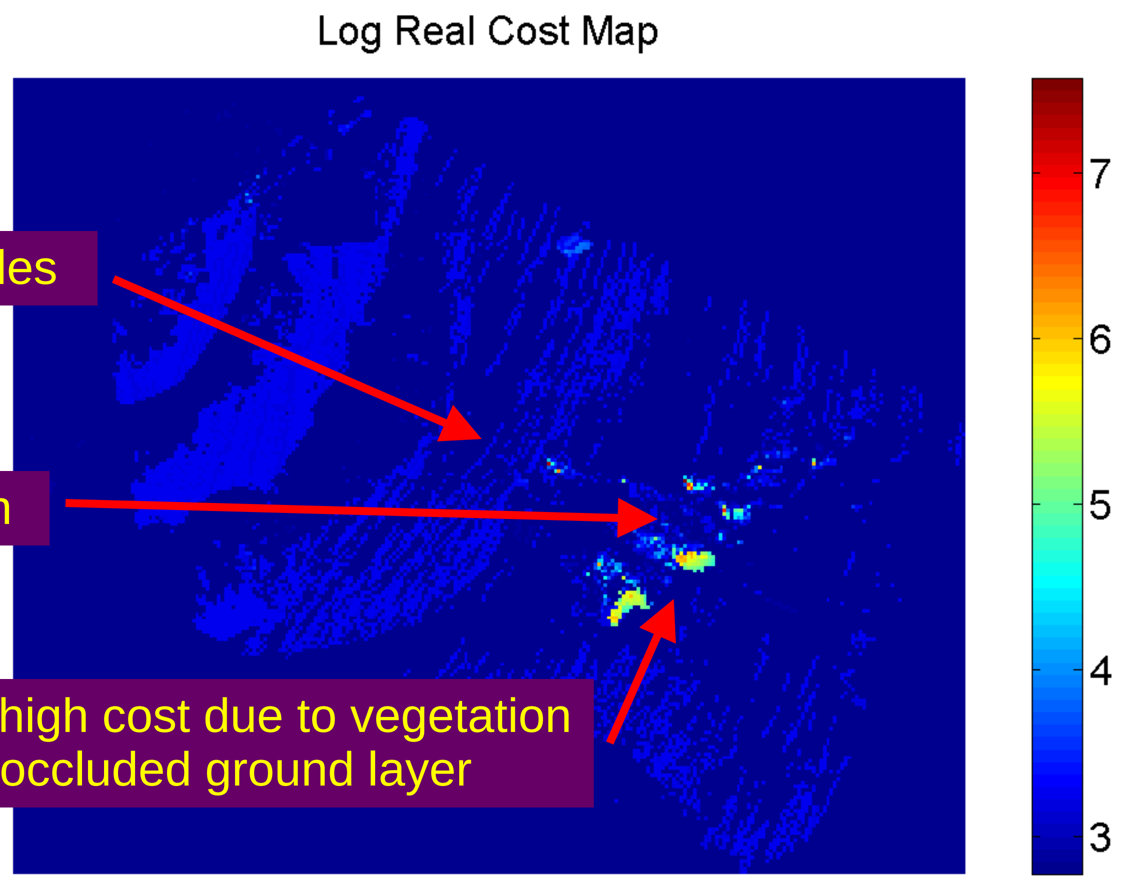
- Visualizations:
  – Log of cost value (to show dynamic range)
- Evaluations
  – Direct pixel subtraction
  – Subtraction with median filtering (reduce edge effects that may occur)

Real Data Cost Map



Higher values indicate higher cost areas ie: areas vehicle prefers not to go through. Log(cost) is shown to show dynamic range

Real Data Cost Map



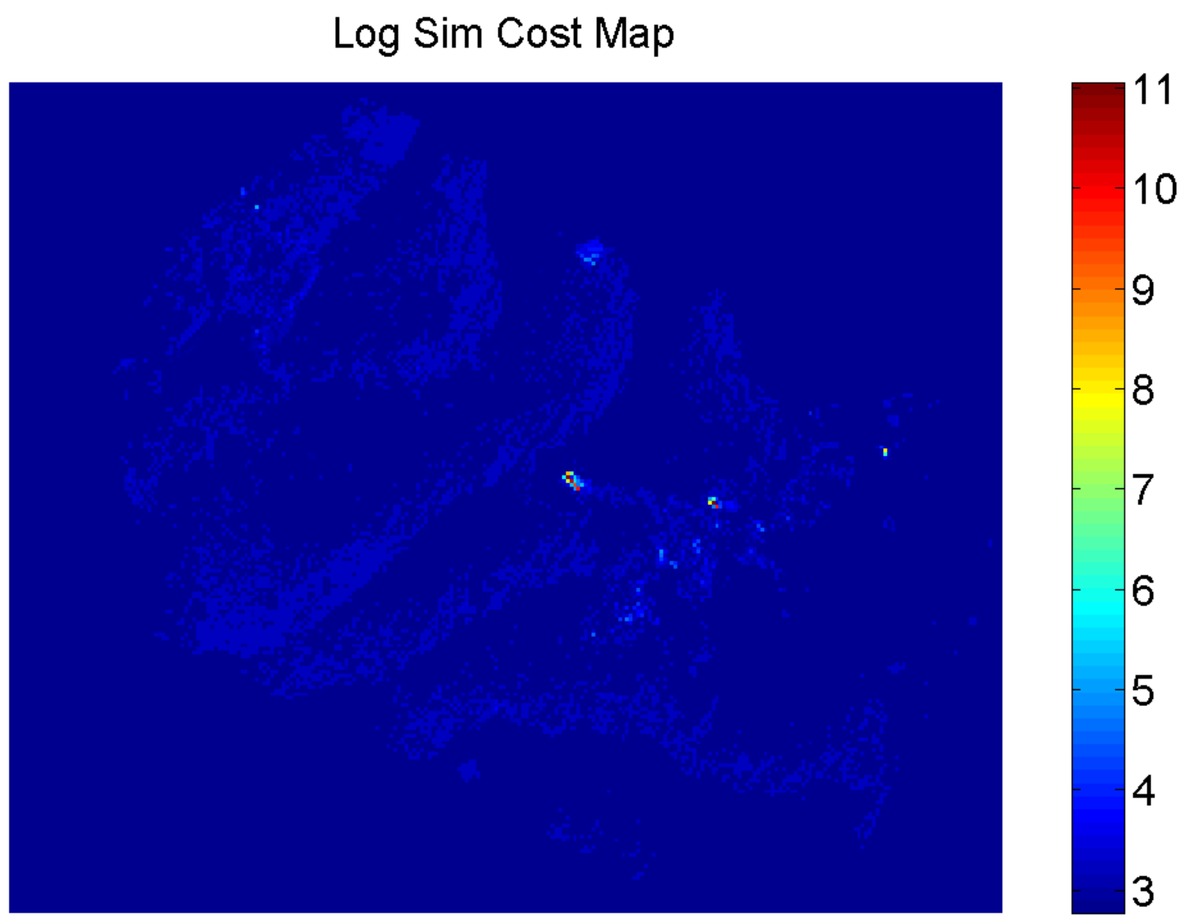
Major obstacles

Vegetation

Areas of high cost due to vegetation and occluded ground layer

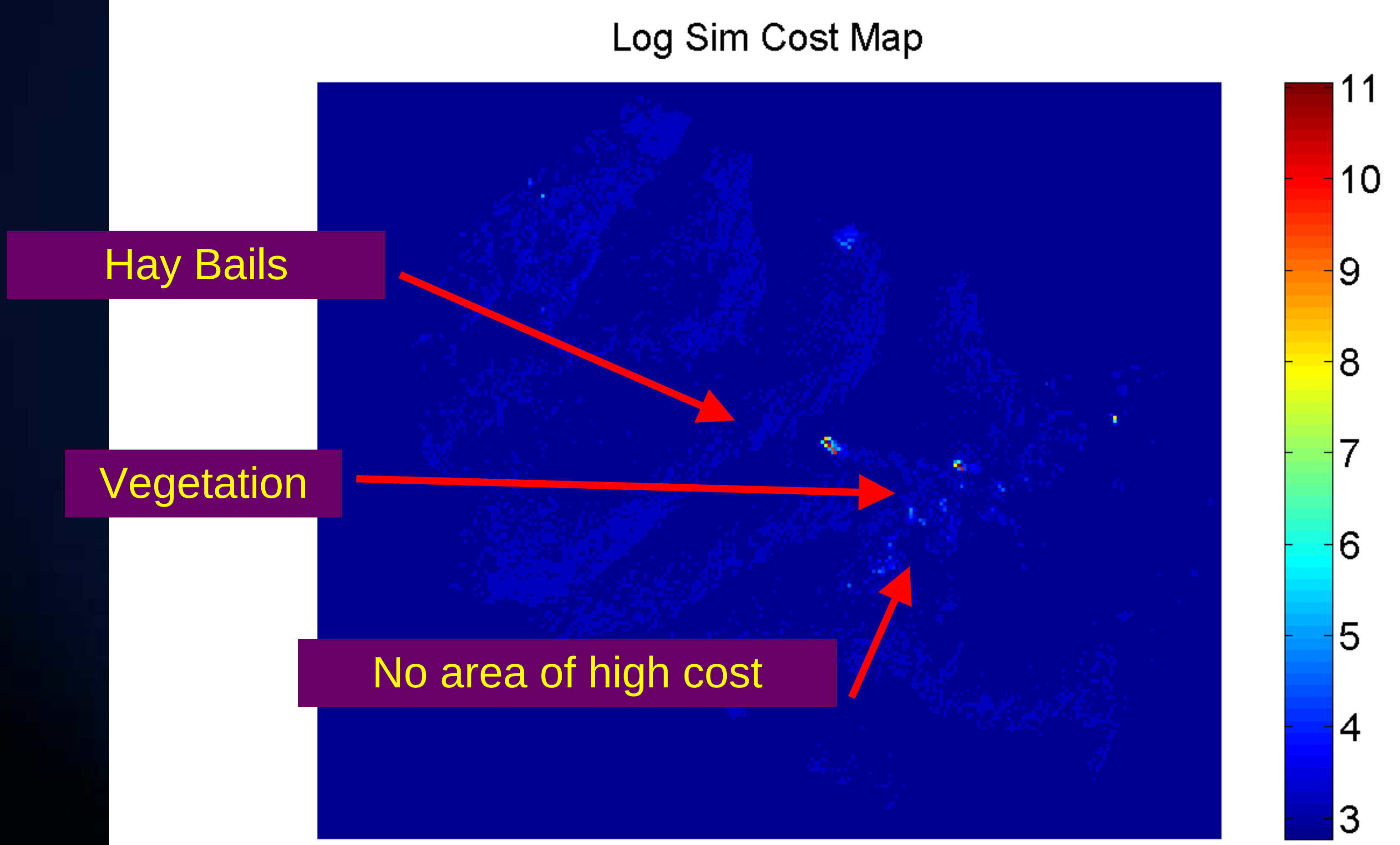
Higher values indicate higher cost areas ie: areas vehicle prefers not to go through. Log(cost) is shown to show dynamic range

Simulated Cost Map



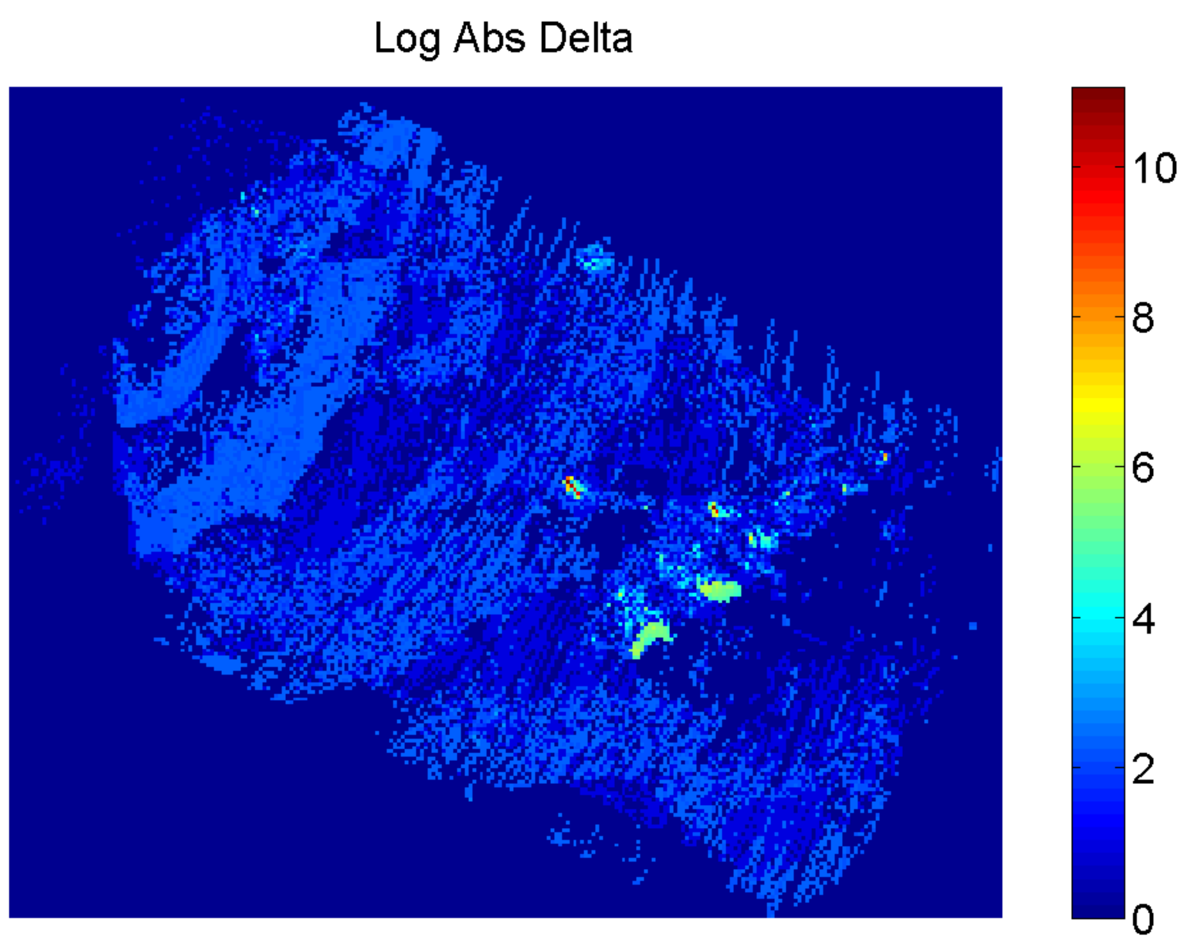
Higher values indicate higher cost areas ie: areas vehicle prefers not to go through. Log(cost) is shown to show dynamic range

Simulated Cost Map



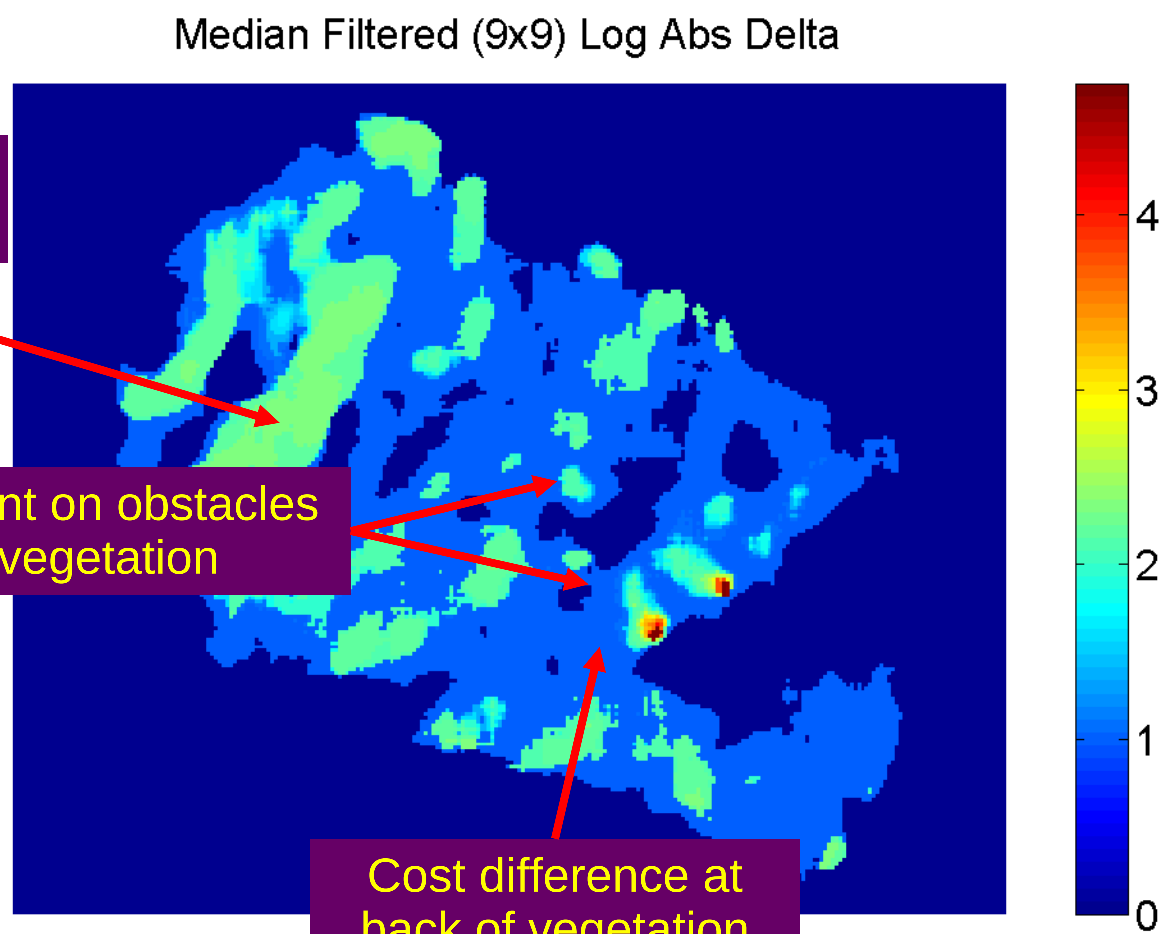
Higher values indicate higher cost areas ie: areas vehicle prefers not to go through. Log(cost) is shown to show dynamic range

Raw absolute Pixel Subtraction



$$\delta(x) = \log\left(\left|Cost_{sim}(x) - Cost_{real}(x)\right|\right)$$

Median Filtered Difference

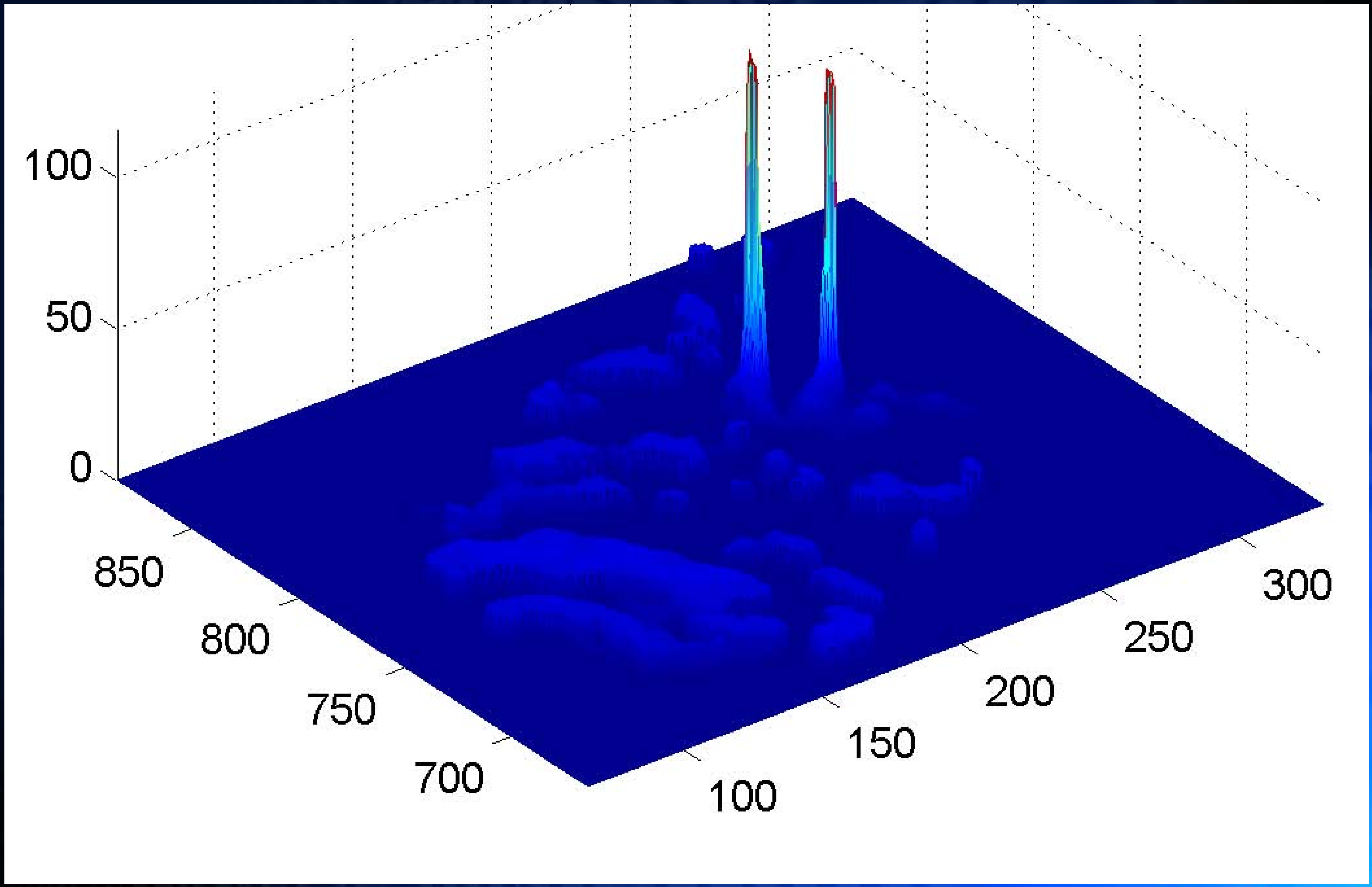


Cost difference is insignificant

General agreement on obstacles and majority vegetation

Cost difference at back of vegetation

Median Filtered Difference (9x9)



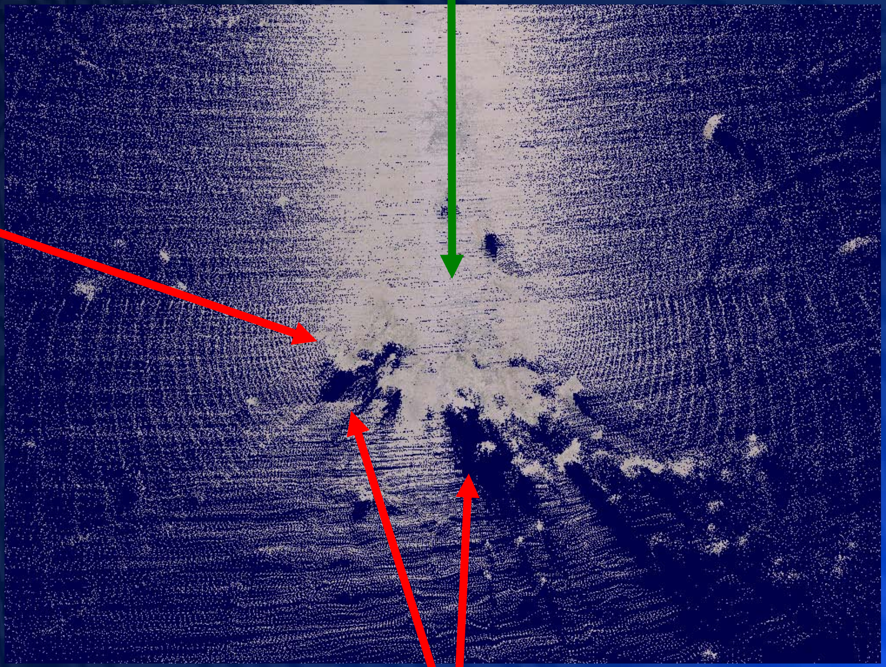
Discussion

- Coarse comparison is good
  - Strong expectation that vehicle will follow same trajectories
  - Geometric obstacles (hay bails) produce very similar costs
- Key cost differences for area just behind vegetation
- Deeper analysis shows higher cost is associated with ground estimation in real data
  - If ground level is inferred by vehicle (vs. directly being observed), cost estimate is higher
- Most likely causes
  - Differences in vehicle pose vs. true vehicle pose relative to ground caused by pose error
  - Different modeled height/size/density of vegetation

Real Data

Vehicle trajectory

Vegetation



Inferred ground height due to occlusion, create higher cost areas

Conclusions

- First phase comparisons are good
  - Strong evidence that vehicle trajectories in simulation will match real vehicle performance
- Some challenges identified
  - Pose error in data collection is an issue
  - No good tools for rapid model building
  - Vegetation differences (for perception) may become a more significant issue in more complex terrain